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Artikel: The rôle of accretionary wedges in the growth of continents : asiatic examples from Argand to plate tectonics

Kapitel: Discussion

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Balkash granitic complex intruded in the arc region, while both flysch and shallow water limestones, and terrestrial clastics were being deposited in the trench/forearc area (Karyayev 1984).

In the late Carboniferous-Permian interval the arc axis shifted only slightly back into the retroarc area, which might indicate imminent collision with a continent and/or another accretionary complex that might have foreshortened the forearc. Full-scale collision indeed was underway with the north Tarim-Tien Shan fragment by the later Permian which switched off arc magmatism and generated an areal, silicic alkalic to subalkalic magmatism associated with continental collision (e.g. the alaskites, alkalic granites, syenites and monzonites of the Bayanaul, Tluembet, Barkanas and Koytas igneous complexes: Karyayev 1984).

Fig. 17 summarizes the way in which the Central Kazakhstan "microcontinent" formed through the Palaeozoic, (for a partly different interpretation, see Markova 1982, fig. 15 and pp. 122ff) and compares it with the evolution of the Kuen-Lun/Songpan-Ganzi system. A third object of comparison displays a present-day example of an accretionary complex, through which arc magmatism migrated during the Mesozoic-Cainozoic interval, namely Japan. In all three cases, the basic story is the same, namely the building out of subduction-accretion complexes in front of backstops of diverse nature and concurrently with the growth of the subduction-accretion complexes, the migration of magmatic arc axes across them in the direction of the ocean. In both the Kuen-Lun and in Kazakhstan, basins seem to have opened in the back-arc area (?back-arc basins) but later closed, before a terminal collision choked the subduction zone that governed the growth of the subduction-accretion complex. In Kazakhstan and in Japan metamorphism of the accretionary complex is mainly of greenschist grade, rising to amphibolite grade only near major plutons and in small relicts of older continental crust that have nothing to do with the metamorphism of the accretionary complex itself (Sobolev et al. 1982; Geological Atlas of Japan 1982). Only in the western Kuen-Lun we have encountered a widespread amphibolite-grade metamorphism that appears to have produced locally migmatites (Wyss 1940). This finds its analogue in the Chugach Mountains accretionary complex of Alaska and may have been related to ridge subduction (Plafker et al. 1989).

Fig. 10 shows the vast areas occupied by accretionary complexes in Asia implying that nearly all of the Altaid Asia formed through processes very similar to those we infer to have governed the evolution of the Kuen-Lun and the Central Kazakhstan ranges. In other words, the Turkic-Style orogeny dominated not only the northern part of the Cimmerides, but also most of the Altaid Asia. In the next section we discuss what this may mean for our understanding of continental growth and architecture.

7. Discussion

7.1 Tectonic analysis of Turkic-type orogens and the palaeotectonics of Central Asia

In the early days of plate tectonics, the Alps and the Himalaya coloured profoundly the popular image of collision-type orogenic belts, in which extremely narrow sutures essentially represented surfaces along which two colliding continents were apposed (cf. Gansser 1966, esp. p. 842; also Dewey & Bird 1970, figs. 2G, 11E, F, G and 13). By

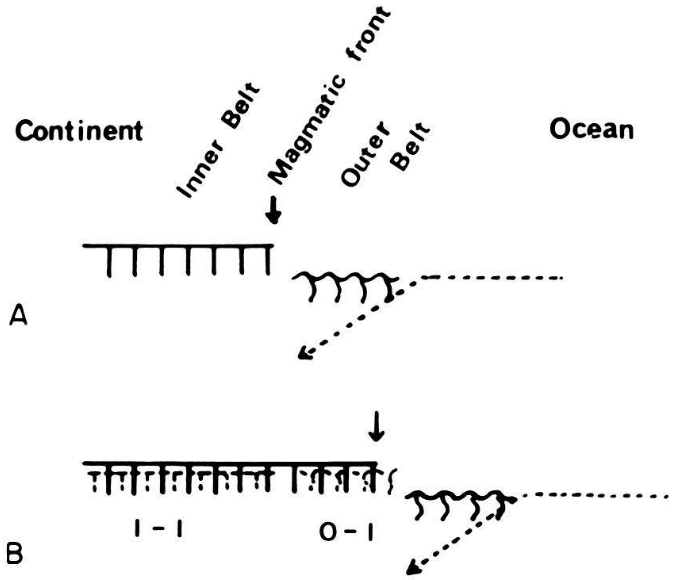

Fig. 18. Overlapping of the inner and outer belts (portion indicated as 0–1), as magmatic front migrates oceanward from stage A to stage B in Japan (from MATSUDA & UYEDA 1971, fig. 6). This is precisely the situation observed in the Kuen-Lun and in Kazakhstan.

contrast, geologists working around the Pacific Ocean, especially those in North America (HAMILTON 1969; HSÜ 1971, 1972), Japan (MATSUDA & UYEDA 1971), Australia (CROOK 1969; RUTLAND 1973, 1976) and New Zealand (LANDIS & BISHOP 1972) knew that the continental edge does not stay fixed during subductive removal of ocean floor and that it may move oceanward with respect to the continental interior by the addition of subduction-accretion material to the original continental margin. MATSUDA & UYEDA (1971) explicitly pointed out that the arc magmatic axis may track the receding trench and eventually come to occupy areas underlain by accretionary material not originally a part of the continent (Fig. 18), and observed prophetically that "It is a task for the future to understand fully the tectonic significance of these migrations and changes of magmatic fronts" (MATSUDA & UYEDA 1971, 0.16). A year later HSÜ (1972 p. 38) christened this kind of accretionary margins "Franciscan subtype" of Pacific-type convergent margins, although he did not emphasize the migration of the arc-related igneous activity to invade former subduction-accretion complexes.

This idea of lateral continental growth by subduction-accretion did not gain much popularity (e.g. RUTLAND 1976), perhaps because of DICKINSON's influential 1973 paper, in which he showed that arc-trench gaps grow with time not only by trench retreat, but also by the retreat of the magmatic axis into the arc internal side, *i.e. away from the ocean*[20]). DICKINSON (1973, table 1) displayed an impressive array of examples, but did not discuss the nature of the *arc basement.* Thus his readers did not realize that in Japan, for example, the magmatic arc was nested on a former subduction-accre-

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[20]) Also most non-Soviet authors were not aware of Peive's and his colleagues' work on the growth of Central Asia in the seventies, which could have helped them to recognize the general applicability of the model put forward by Matsuda and Uyeda and Hsü.

tion complex, which, for time intervals longer than those considered by Dickinson (1973), essentially invalidated his thesis. Neither did Dickinson (1973) consider very wide extant forearc wedges such as Makran (600 km arc-trench separation in Pakistan: Şengör 1990a). In 1977, however, Dickinson paid a visit to Japan and was quick to realize that indeed the arc massif at least in southwestern Japan was formed by what he called "Palaeopacific oceanic facies", thus corroborating Matsuda & Uyeda's (1971) earlier inference (Dickinson 1977, esp. fig. 2 and p. 950ff). Dickinson (1977) further generalized this picture to much of the western U.S. Cordillera.

As work in such places as Alaska progressed, however, Matsuda & Uyeda's (1971), and Dickinson's (1977) – and indeed Peive's and his collaborators' – point began to receive wider recognition that arc massifs themselves indeed may be made up of old subduction-accretion complexes and such complexes, now intruded by arc plutons, covered by arc volcanics plus intra-arc basin deposits in addition to older forearc and/or inner trench slope deposits, and in places finally invaded by collision-related magmatic rocks, may occupy huge areas and make up much of the continental crust of certain orogens (e.g. Jones et al. 1982, 1987). Because subduction-accretion complexes habitually contain diverse slivers of ophiolites and/or deep-sea deposits, in a confusing array of thrust fault-bounded packages, ophiolite trains in such terrains lose their reliability as suture zone indicators. Large, along-strike sideways motion characterizes many of the active subduction-accretion complexes (e.g. Karig 1980; Moore & Silver 1983, esp. fig. 10) and similar faults probably also affected older ones, perhaps intercalating arc magmatics into even the distal parts of coeval subduction-accretion complexes.

One can readily appreciate the grave difficulties of trying to define tectonic units and to identify past plate tectonic environments in such a mess of highly deformed oceanic, trench and arc-trench gap sedimentary rocks, arc, collisional, and even perhaps rift magmatics, where reliable tracers such as shelf/slope breaks of normal Atlantic-type continental margins or Indus-type clean suture zones are absent. Obruchev's (1915, plate I) graphic summary of the disparate views concerning the orientation of the dominant trend-lines in the Russian Altay proposed between 1833 and 1914 is a remarkable document displaying the difficulties of tectonic synthesis in regions dominated by subduction-accretion/magmatic arc complexes. It was the frustration encountered in such terrains in the western North America and Alaska, which had refused to fit into the neat Alpine, Himalayan, or the Andean straightjackets, which derailed regional tectonic research into the seductive labyrinth of terranology (cf. Şengör 1990b; Şengör & Dewey 1990). It is easy to see the need for the comfort of alleviating "the immediate necessity of incorporating every facet of geologic development in a single encompassing model" (Williams & Hatcher 1983, p. 34) in a place where every other outcrop turns out to be a multiply deformed chert/slate/greywacke succession, here overlain by reefal limestone, there intruded by a granodiorite stock, in yet another place cooked up to amphibolite grade! But, we think, precisely in such monotonously chaotic places does the geologist need a good working model to guide him out of a maze of detailed but unconstraining observations to arrive at a final synthetic understanding.

For an understanding of the palaeotectonic evolution of Central Asia, including the whole of the Altaids and the northern moeity of the Cimmerides, we suggest, therefore, that we view them in the light of the accumulation and consolidation of giant subduction-accretion complexes (for a similar early suggestion for only the western part of the Altaids, see Dickinson 1974, esp. fig. 10), whose oceanward growth is commonly tracked by the migration into them of arc magmatic axes. Present-day examples of such huge accretionary complexes are not many, being confined to Alaska, Makran, Barbados, and the eastern Mediterranean, but both Alaska and Japan contain well-studied and long-lived examples.

In tectonic collages dominated by Turkic-type orogenic belts, the first step in tectonic analysis would be to map out the arc axes and then to delimit the various accretionary complexes whose collisional agglomeration would be the final stage in the growth of the collage. No clean ophiolitic sutures would exist in such places (because ophiolite slivers are commonly found throughout the "basement!") and suture locations would have to be inferred using other means than tracing neat and clean ophiolitic outcrop trains bordering well-defined and narrow magmatic arc belts of the type Indus/Transhimalaya suture/arc couple. The grave difficulty of finding sutures in such settings is perhaps best exemplified by the fact that no suture line can be identified between the Sengihe and Halmahera island arcs whose large accretionary forearcs collided only in the course of the Quaternary (Silver & Moore 1978; Hamilton 1979).

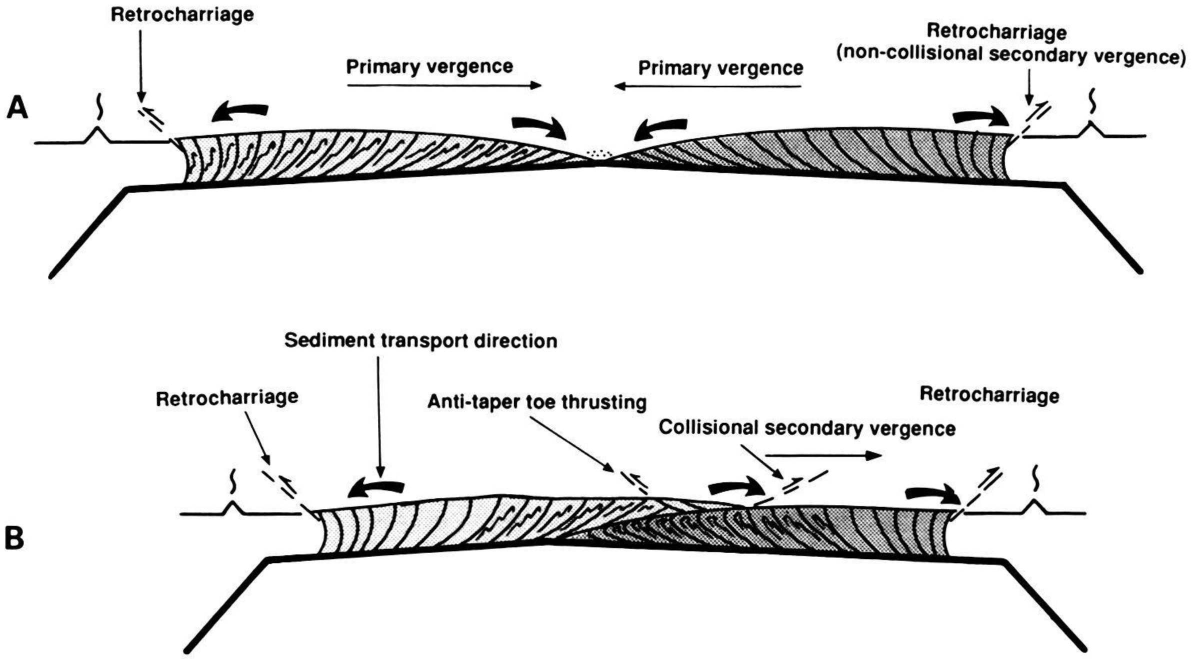

Fig. 19. Collision of two accretionary wedges. A. The situation just before the collision: In both wedges, the primary vergence is generally oceanward with secondary vergence developing locally in places where anti-taper toe thrusting (shown in B) or backthrusting behind outer non-volcanic highs occur. In case of anti-taper toe thrusting, the secondary vergence and sediment provenance have opposite senses. In case of backthrusting behind non-volcanic outer highs sediment provenance and secondary vergence have the same senses. B. The situation after the collision: Collision-induced secondary vergence is antithetic to anti-taper toe thrusting of the overriding wedge and synthetic to backthrusting behind outer non-volcanic high of the underthrusting wedge. Collision-induced sediment provenance and sediment provenance from outer non-volcanic highs into former forearc areas are the same, but may have small differences in sediment composition. See text for further discussion.

Neither is it possible to identify this suture farther north, in Mindanao, where the collision was in the late Miocene and the region is now subaerial (cf. Şengör 1990a).

Only combined sedimentological/structural studies perhaps coupled with careful seismic reflexion profiling may aid in locating sutures between two collided subduction-accretion complexes by documenting abrupt and regional reversals of vergence overprinting an older, uniformly-vergent but multiply-deformed package, accompanied by a reversal of clastic provenance. This reversal would likely occur under abyssal conditions, where the toe regions of subduction-accretion complexes habitually reside (Fig. 19). This would provide one criterion to distinguish this sort of collision-induced vergence reversal from retrocharriage behind outer non-volcanic highs along the margins of forearc basins (Fig. 19B; except in such unusual cases as the 7 km-deep Weber forearc: Hamilton 1979). Coeval reversal of clastic sediment provenance would discriminate between anti-taper toe thrusting (Seely 1977) and collisional vergence flip (Fig. 19B).

Another guide that might constrain the location of the suture between two colliding accretionary complexes might be the detailed detrital mineralogy of the arenaceous components of the colliding forearc prisms. This difference would disappear, however, shortly before the collision, and could only constrain the location of the suture within a broad zone.

The best way to locate the suture in such areas is to reconstruct the individual accretionary complexes to their pre-collisional geometry using structural, sedimentologic and partly petrologic criteria in the light of their presently active examples. This would mean a model-guided iterative field study that avoids purely descriptive cataloging of rocks in the field, but undertakes description and model-building simultaneously, in a manner reminiscent of William Morris Davis' "explanatory description" of landforms (Davis 1912).

7.2 Turkic-type orogenic belts and the composition of the lower continental crust

If continents may be significantly enlarged by the growth of subduction-accretion complexes through the mechanism depicted in Figs. 17 and 18, then one would expect a fairly uniform pelitic composition of the entire undifferentiated "new" continental crust thus formed, because shales form more than 60% of the world sediment repository (Potter et al. 1980) and pelitic material forms over 70% of all pelagic sediments deposited in the world ocean (Lisitzin 1972), a part of which gets accumulated in subduction-accretion prisms.

Methods to estimate the composition of the lower continental crust are either direct, based on relatively rare exposures of the lower crustal rocks mostly in orogenic belts and on lower crustal xenoliths brought up by igneous processes, or indirect, based either on geophysical observations of seismic velocities and heat flow or on theoretical mass balance calculations. Most petrologic and geophysical models infer a mostly mafic, anhydrous, unradiogenic, and, relative to the upper crust, incompatible element-depleted lower crust, yet many exposed high grade terrains, presumably of lower crustal origin, have pelitic protoliths showing none of the above characteristics (Fountain & Salisbury 1981; Percival & Card 1983). The fact that the average continental crust is more silicic than it ought to be if it indeed came out of the mantle led some to suppose that to achieve this composition, the lower, mafic crust must be delaminated away to "subtract" the residual mafic component following igneous differentiation in zones of crustal thickening (e.g. TURCOTTE 1989).

The dominance of Turkic-type orogens in substantial areas of the continental crust such as Central Asia, where variously modified subduction-accretion complexes form the continental crust, may be one important way of making a crust more silicic than basalt. As REID et al. (1989) emphasized, although basalts are parental to continental crustal growth, and MCKENZIE & O'NIONS (in press) have shown that this growth is dominated by calc-alkalic basalts generated in island arcs above descending slabs, individual continents may be enlarged and thus substantial areas of continental crust may be structured by sedimentary/structural processes involved in the construction of subduction-accretion complexes. MCKENZIE & O'NIONS (in press) pointed out, on the basis of the inversion of NANCE & TAYLOR'S (1976) analyses of post-Archean shales, that their mean rare-earth element concentrations indicate that the melting conditions (mainly in the garnet peridotite stability field, but in the presence of 40% amphibole peridotite, generating melt fractions of about 0.4%), were essentially the same as those that produced the calc-alkalic basalts from Java. The erosion of the parental igneous rocks that culminated in the production of the shales, the transport of the shales into the oceans, where they make up 70% of all pelagic sediment, and the final incorporation of those shales into subduction-accretion complexes is the modern view of the old cycle glyptogenesis → lithogenesis → orogenesis (HAUG 1921) that generates the continental crust.

To what extent this cyclical process actually has added to the bulk of Asia in the Phanerozoic through the construction of the Altaids can be directly assessed by isotopic methods such as a careful measurement of the Nd-Sm model ages of the shales being eroded from the Altaids. The finer size fraction of the fluvial sediments carried by the Irtysh-Ob river system is in this regard an ideal target to establish the Nd-Sm model age of the entire Altaid tectonic collage, although isotopic sampling of limited areas within the Altaid collage has begun to indicate already that in considerable regions the continental crust was made entirely during the Palaeozoic (e.g. KWON et al. 1989).

What this discussion does not consider is how much igneous rock gets underplated beneath subduction-accretion complexes when they become sites of arc magmatism or ridge subduction, or post-collisional magmatism. We suspect that it eventually must amount to significantly less than 50%, because many well-developed magmatic subduction-accretion complexes today have mature thicknesses at or near the continental average of about 30–35 km. Underplating must also be a spatially heterogeneous process, because arc axes prograde oceanward commonly in discrete jumps and rarely in continuous sweeps.

7.3 Turkic-type orogenic belts and the structure of the lower crust

One important characteristic of many subduction-accretion complexes is that in addition to frontal accretion, much sediment is dragged down under the accretionary prism (BANGS & WESTBROOK 1991), of which a part gets underplated (e.g. CLOOS & SHREVE 1988) and the rest subducted (e.g. MOORE 1975). The sediments dragged down

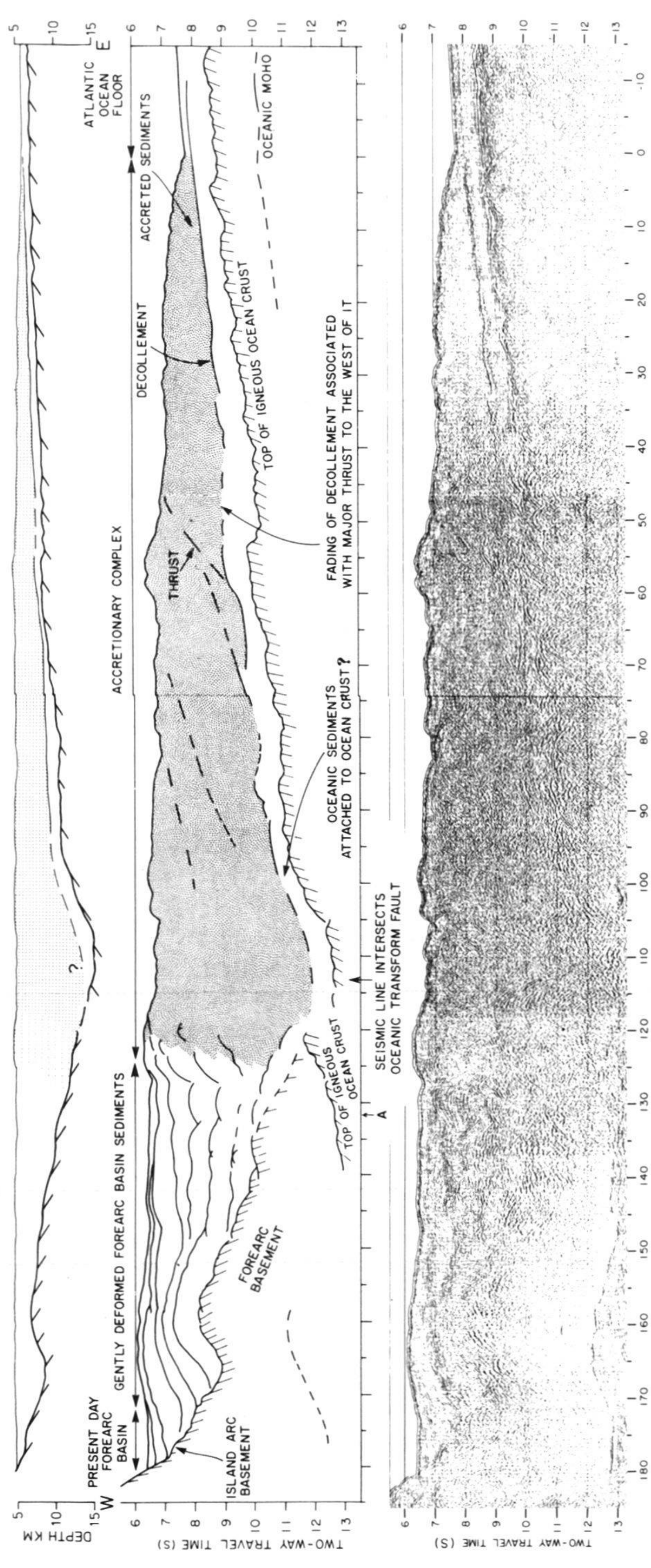

Fig. 20. A seismic reflexion profile across the Barbados accretionary complex (after Westbrook et al. 1988). Notice the distinct layering along the base of the wedge and how the lateral continuity of that layering deteriorates towards the back of the wedge, passing into broadly arched reflexions first (between 20 and 35 km) and then into crossing arcuate events (behind 35 km). Discussion is in the text.

under the accretionary complexes commonly give rise to near planar to very broadly undulating reflectors near the toe of the accretionary complex (Fig. 20; for details see BANGS & WESTBROOK 1991, fig. 5). The reflectors become broadly arched near the middle of the wedge and finally deteriorate into crossing arcuate events near the backstop in the rear parts of the accretionary complex. These are three of the four classes of reflexion response of the lower crust distinguished by SMITHSON (1986). BANGS & WESTBROOK (1991) were able to trace the decollement horizon for 108 km from the toe of the Barbados wedge, i.e. about half its width. Farther back, the decollement horizon becomes deformed mainly by thrusting. Following a collision, the near planar to very broadly undulating reflectors are unlikely to survive as such and would probably turn into either broadly arched or crossing arcuate reflexion events, depending on the intensity of the deformation. Massive intrusions into the accretionary complex would also destroy a part of the reflectors created by sediment underthrusting. It is likely, however, that segments of these reflectors would survive syn- and post-collisional convergence and orogenic magmatic events and would appear as "lower crustal reflectors" under the well-developed, thick accretionary complexes such as that of the Olympic Peninsula in the northwestern United States (thickness under the Peripheral Fault about 40 km!: BRANDON & CALDERWOOD 1990) which themselves would be largely acoustically opaque owing to the complex state of the deformation in them. MOORE & SILVER (1983) display in their fig. 9 such a prominent group of broadly arched reflectors between 5.5 and 6.5 seconds beneath the Molucca Sea collided accretionary complex west of the Snellius Ridge. More recently the BABEL WORKING GROUP (1990) has published a seismic reflexion profile across the Svecofennides in the Baltic Shield, in which crossing arcuate events were interpreted as representing lower parts of a fossil accretionary complex (see BABEL WORKING GROUP 1990, figs. 3a, b, and 5). WINDLEY (1991) interprets the Svecofennides in a manner similar to our interpretation of the Altaids and has suggested that they may be a Proterozoic analogue of the Altaid collage (Prof. B.F. WINDLEY, pers. comm. 1991).

Sediment underthrusting and underplating – even underplating of parts of the oceanic crust – under accretionary complexes provides a way of creating laterally persistent reflectors (between > 100 and 50 km across-strike width, if the present Barbados decollement and the 50% post-collisional shortening in Tibet are taken as possible extremes) at depths ranging from a few to 30 km underlying a highly deformed and diffractive crust, where surface geology would give no indication whatever that laterally continuous reflectors might exist at mid- to lower crustal depths.

8. Conclusions

The main conclusion of this study is that very substantial continental enlargement – not necessarily continental "growth" as this term is now commonly understood – by subduction-accretion has been likely a common process responsible for the primary structuration of the continental crust in the history of our planet as exemplified by the late Proterozoic to middle Mesozoic tectonic history of its largest continent, Asia. As subduction-accretion complexes grow, three main processes contribute to their consolidation and augmentation of their thickness. In decreasing importance these are: 1) Invasion of former forearc areas by arc plutons by the trenchward shifting of the mag-